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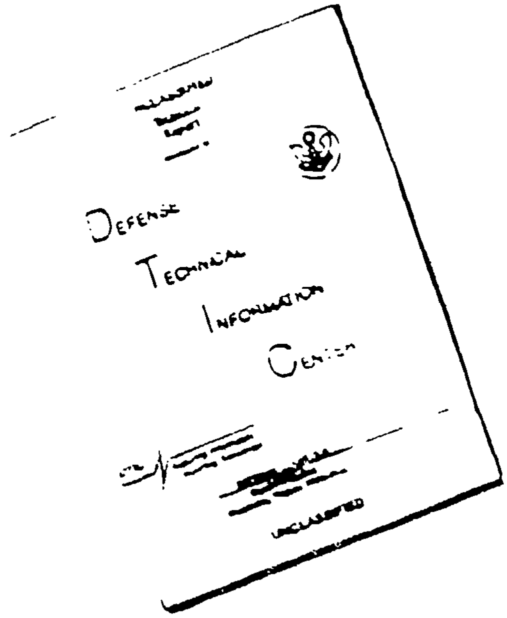
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The Antenna Laboratory

Department of Electrical Engineering

Fourth Quarterly Progress Report

EFFECTS OF TYPE OF POLARIZATION ON ECHO CHARACTERISTICS

Contract AF 28 (099)-90

For Period Ending 15 June 1950

WATSON LABORATORIES, AIR MATERIEL COMMAND
RED BANK, NEW JERSEY

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16 June 1950

The Ohio State University
Research Foundation
Columbus, Ohio

PROJECT REPORT 389-4

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THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

COLUMBUS 10, OHIO

Cooperator	Watson Laboratories, Air Materiel Command Red Bank, New Jersey 3151 Electronics Station
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Investigation of	Effects of Type of Polarization on Echo Characteristics
Subject of Report	Fourth Quarterly Progress Report For Period Ending 15 June 1950
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EFFECTS OF TYPE OF POLARIZATION
ON ECHO CHARACTERISTICS

EFFECTS OF TYPE OF POLARIZATION ON ECHO CHARACTERISTICS

A. ABSTRACT

By the use of a scattering matrix the dependence of echo upon transmitting and receiving antenna polarizations for a particular radar target can be described by the variation in absolute value of a complex bilinear form. From a study of this expression the antenna polarizations which yield maximum return, as well as those which yield zero return signal, may be found. The discrimination that a particular choice of antenna polarizations gives between a desired target and an undesired target, such as rain clutter, can also be studied quantitatively by this means. A consistent method of identifying targets by their scattering properties is also indicated.

A graphical means of presenting polarization dependence of target echo is desirable in the analysis of response from more than one target, or more than one aspect of a given target. Since the polarization yielding maximum return from a target varies as that target changes in aspect, the best polarization for a range of aspects must be selected. The graphical analysis of such data is made possible by use of a polarization chart, on which each point corresponds to a particular antenna polarization. Points on constant echo curves represent polarizations for which the echo is constant, and the areas common to these curves for several targets may be studied to select the over-all optimum polarization. Several types of polarization charts are studied, and the relation of these charts to a three-dimensional polarization chart on a sphere is shown.

Determination of the scattering matrix of a particular radar target is best made by means of a model method such as used at the Antenna Laboratory of the Department of Electrical Engineering, The Ohio State University. The scattering matrix contains important phase factors which must be determined. The measuring technique is greatly simplified if the desired information can be obtained solely from amplitude measurements.

A method of determining the amplitudes and phases of the components of a target scattering matrix by amplitude measurements alone is discussed. Seven amplitude measurements must be made to completely determine the scattering matrix.

Apparatus for measuring the scattering matrix has been developed, and several

preliminary tests are described.

B. PURPOSE

This Fourth Quarterly Progress Report is to be a summary of the theoretical studies of the effects of antenna polarization upon echo characteristics made during the period 15 June 1949 to 15 June 1950.

C. FACTUAL DATA

1. THEORETICAL STUDIES

a. Use of Scattering Matrix

(1). Description of Coordinate Axes and Polarization

Since several methods of representing the polarization of an elliptically polarized wave are in use at present, the convention used in this discussion will be defined.

Consider the coordinate system shown in Fig. 1, with a target located at the origin, and the transmitter at a large distance r from the origin along the z-axis. In a plane perpendicular to the z-axis, two orthogonal unit vectors are chosen to define the positive θ and ϕ directions. At a point P, where the polarization of a wave traveling along the z-axis is to be studied, two identical, coplanar, linearly polarized dipole antennas are placed parallel to the θ and ϕ directions. The voltages induced in the θ and ϕ directed dipoles are represented by $\mathcal{E}_\theta$ and $\mathcal{E}_\phi$. These two voltages may be expressed in complex notation by:

$$\begin{aligned} \mathcal{E}_\theta &= E_\theta\, e^{j\,\delta/2} \\ \mathcal{E}_\phi &= E_\phi\, e^{-j\,\delta/2} \end{aligned} \qquad (1)$$

where E_θ and E_ϕ are real and positive, and δ is the phase lead of $\mathcal{E}_\theta$ over $\mathcal{E}_\phi$. The two magnitudes, E_θ and E_ϕ, and the phase angle plus the direction of propagation, describe the wave completely. If a wave traveling from the transmitter toward the target (or origin) is denoted by the superscript "t", and a wave traveling from the target (or origin) by the superscript "r", then a transmitted wave which induces voltages $\mathcal{E}_\theta$ and $\mathcal{E}_\phi$ in the test antenna would be represented as a two-component vector:

$$E^t = \begin{pmatrix} \mathcal{E}_\theta^t \\ \mathcal{E}_\phi^t \end{pmatrix} . \qquad (2)$$

Similarly, a reflected wave which induces the same voltages in the test antenna would be represented by

$$E^r = \begin{pmatrix} E_\theta^r \\ E_\phi^r \end{pmatrix} \tag{3}$$

A transmitted and reflected wave represented by the same two components in this reference system will actually have polarization ellipses which are inclined at supplementary angles to the common reference axis and have opposite senses of rotation, looking in the direction of propagation in each case.

(2). The Scattering Matrix

In general, the polarization of a plane wave which falls upon a radar target is changed upon reflection. This is due to two phenomena: selective reflection of the several components of the incident wave; and coupling between one component of the incident wave and the orthogonal component of the reflected wave. If

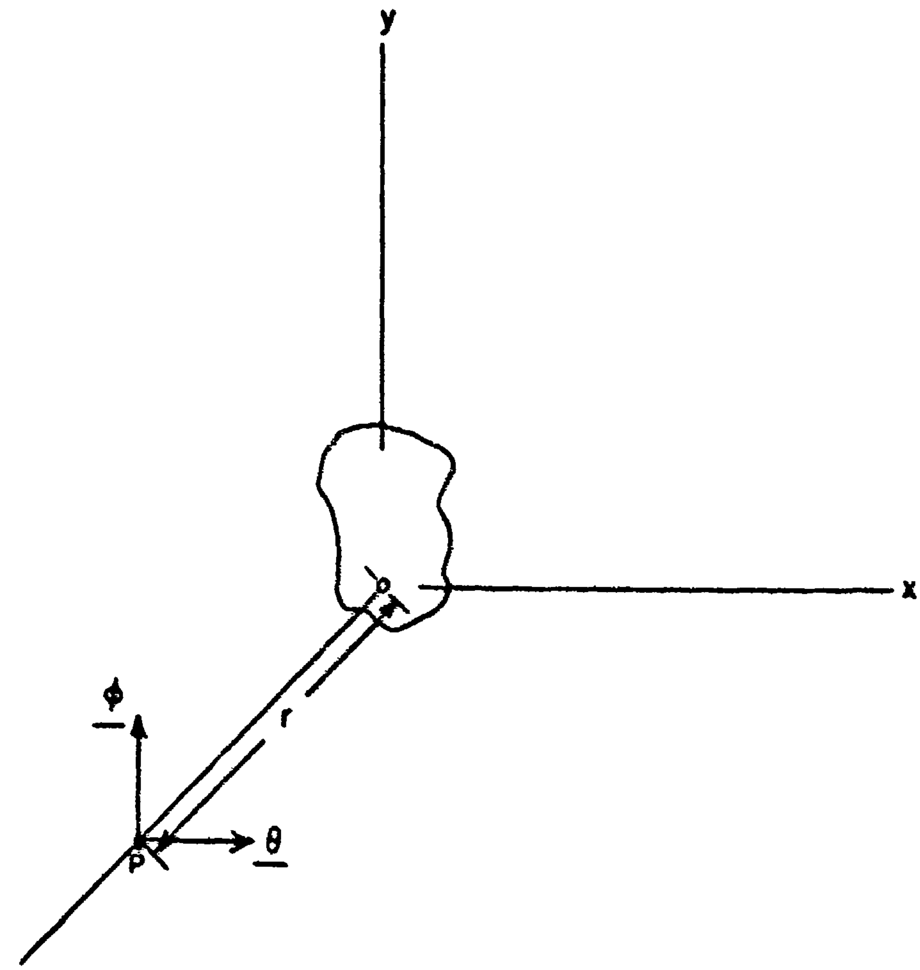


Fig. 1 Coordinate system.

the incident plane wave is linearly polarized in the θ direction, then

$$\mathbf{E}_1^t = \begin{pmatrix} E_\theta^t \\ 0 \end{pmatrix} \quad . \tag{4}$$

The reflected wave at a large distance r from the origin is essentially spherical and contains only transverse components which can be measured by the test antenna as

$$\mathbf{E}_1^r = \begin{pmatrix} E_{\theta_1}^r \\ E_{\phi_1}^r \end{pmatrix} \quad . \tag{5}$$

The components of the reflected wave are related to the incident wave linearly:

$$\begin{aligned} E_{\theta_1}^r &= (a_{11}\, E_\theta^t) \frac{1}{\sqrt{4\pi\, r^2}} \\ E_{\phi_1}^r &= (a_{21}\, E_\theta^t) \frac{1}{\sqrt{4\pi\, r^2}} \quad , \end{aligned} \tag{6}$$

where

$$\begin{aligned} a_{11} &= \frac{E_{\theta_1}^r}{E_\theta^t} \sqrt{4\pi\, r^2} \\ a_{21} &= \frac{E_{\phi_1}^r}{E_\theta^t} \sqrt{4\pi\, r^2} \quad . \end{aligned} \tag{7}$$

Similarly, if the incident wave is linearly polarized in the ϕ direction,

$$\mathbf{E}_2^t = \begin{pmatrix} 0 \\ E_\phi^t \end{pmatrix} \quad , \tag{8}$$

the reflected wave at a large distance r would be given by

$$\mathbf{E}_2^r = \begin{pmatrix} E_{\theta_2}^r \\ E_{\phi_2}^r \end{pmatrix} \quad , \tag{9}$$

where

$$\begin{aligned} E_{\theta_2}^r &= (a_{12}\, E_\phi^t) \frac{1}{\sqrt{4\pi\, r^2}} \\ E_{\phi_2}^r &= (a_{22}\, E_\phi^t) \frac{1}{\sqrt{4\pi\, r^2}} \quad . \end{aligned} \tag{10}$$

and

$$
\begin{aligned}
a_{12} &= \frac{E^r_{\theta_2}}{E^t_\phi}\sqrt{4\pi\, r^2} \\
a_{22} &= \frac{E^r_{\phi_2}}{E^t_\phi}\sqrt{4\pi\, r^2} \quad .
\end{aligned}
\tag{11}
$$

By the superposition theorem, if the incident wave were to consist of both linearly polarized components

$$
\mathbf{E}^t = \mathbf{E}^t_1 + \mathbf{E}^t_2 = \begin{pmatrix} E^t_\theta \\ E^t_\phi \end{pmatrix} \quad , \tag{12}
$$

the reflected wave will be given by,

$$
\mathbf{E}^r = \mathbf{E}^r_1 + \mathbf{E}^r_2 = \begin{pmatrix} E^r_{\theta_1} + E^r_{\theta_2} \\ E^r_{\phi_1} + E^r_{\phi_2} \end{pmatrix} \quad . \tag{13}
$$

or in matrix notation,

$$
\mathbf{E}^r = \begin{pmatrix} E^r_\theta \\ E^r_\phi \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} E^t_\theta \\ E^t_\phi \end{pmatrix} \frac{1}{\sqrt{4\pi\, r^2}} \quad . \tag{14}
$$

The matrix

$$
A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \tag{15}
$$

is known as the scattering matrix,[1] and completely determines the polarization transforming properties of the target in the reference direction by the equation

$$
\mathbf{E}^r = A\, \mathbf{E}^t \frac{1}{\sqrt{4\pi\, r^2}} \quad . \tag{16}
$$

(3). Vector Antenna Height

In a given direction the transmitting and receiving properties of an antenna may be described by a two-component vector height so defined that, if the antenna is used for transmitting, the values of the two transverse components of transmitted field at a large distance r from the antenna in the reference direction are given by:

$$
\begin{aligned}
E^t_\theta &= \frac{Z_0\, I_t}{2\lambda\, r} h^t_\theta \\
E^t_\phi &= \frac{Z_0\, I_t}{2\lambda\, r} h^t_\phi \quad .
\end{aligned}
\tag{17}
$$

neglecting a common phase factor which depends upon the distance. Z_o is the impedance of free space, I_t the terminal antenna current, λ the wavelength, and h_θ and h_ϕ are the components of vector antenna height in the positive θ and ϕ directions respectively. This relation may be expressed in vector notation as:

$$\mathrm{E}^t = \mathrm{h}^t \frac{Z_o I_t}{2\lambda r} \quad . \tag{18}$$

If the antenna is used for receiving, the value of the terminal voltage developed by an arbitrary plane wave incident upon the antenna from the reference direction is

$$V_r = E_\theta^r h_\theta^r + E_\phi^r h_\phi^r = \mathrm{E}^r \cdot \mathrm{h}^r \quad , \tag{19}$$

where the vectors h^r and h^t are identical for the same antenna.

Combining the relations

$$\begin{aligned} \mathrm{E}^t &= \frac{Z_o I_t}{2\lambda r} \mathrm{h}^t \\ \mathrm{E}^r &= A \, \mathrm{E}^t \frac{1}{\sqrt{4\pi r^2}} \\ V_r &= \mathrm{E}^r \cdot \mathrm{h}^r \quad . \end{aligned} \tag{20}$$

the equation

$$V_r = \frac{Z_o I_t}{4\lambda r^2 \sqrt{\pi}} \mathrm{h}^r A \, \mathrm{h}^t \tag{21}$$

is obtained. For a given input power and target range, the magnitude of the received voltage is proportional to a quantity Q, where

$$Q = |\mathrm{h}^r A \, \mathrm{h}^t| \quad . \tag{22}$$

The vertical lines denote absolute magnitude of the enclosed quantity, h^t is the vector height of the transmitting antenna, h^r is the vector height of the receiving antenna, and A is the scattering matrix of the target. For a given input power to transmitting antenna, the received power is proportional to

$$Q^2 = \left| (h_\theta^r \; h_\phi^r) \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} h_\theta^t \\ h_\phi^t \end{pmatrix} \right|^2 \quad . \tag{23}$$

It is sufficient to study the behavior of Q^2 for various choices of h^r and h^t, to determine the response of the antenna-target system for various types of polarization.

Since, in practice, the effective receiving or transmitting area of the antenna is limited, the condition that the absolute values of h^t and h^r be equal to unity is also imposed. Using the equation for V_r

$$V_r = \frac{Z_o\, I_t}{4\lambda\, r^2\sqrt{\pi}}\, h^r\, A\, h^t\,, \tag{24}$$

the received voltage for a θ directed, linearly polarized transmitting antenna, and a φ directed, linearly polarized identical receiving antenna is

$$V_r = \frac{Z_o\, I_t}{4\lambda\, r^2\sqrt{\pi}}\, a_{21}\quad . \tag{25}$$

If transmitter and receiver are interchanged, the voltage is

$$V_r = \frac{Z_o\, I_t}{4\lambda\, r^2\sqrt{\pi}}\, a_{12}\quad . \tag{26}$$

By the reciprocity theorem, these must be the same. Hence the scattering matrix is symmetric, and $a_{12} = a_{21}$.

Instead of two orthogonal linearly polarized antennas two orthogonal elliptically polarized antennas might be used to define the scattering matrix.[2] If the vector height of one elliptically polarized antenna in a linearly polarized reference system is given by

$$h_1 = \begin{pmatrix} h_\theta \\ h_\varphi \end{pmatrix}\quad , \tag{27}$$

the elliptically polarized wave which it best receives would have components

$$E^r = \begin{pmatrix} h_\theta^* \\ h_\varphi^* \end{pmatrix} \tag{28}$$

where the asterisks denote complex conjugates.[3] The antenna orthogonal to h_1 would not detect this wave, hence

$$h_2 \cdot E^r = 0, \quad h_2 = \begin{pmatrix} -h_\varphi^* \\ h_\theta^* \end{pmatrix} e^{j\delta} \tag{29}$$

where δ is arbitrary, defines the orthogonal antenna. To determine the scattering matrix relative to the new orthogonal elliptically polarized reference vectors h_1 and h_2 form the products

$$a'_{11} = \mathrm{h}_1 A \mathrm{h}_1$$
$$a'_{21} = a'_{12} = \mathrm{h}_1 A \mathrm{h}_2 \qquad (30)$$
$$a'_{22} = \mathrm{h}_2 A \mathrm{h}_2 \quad ,$$

where A is the scattering matrix expressed in an orthogonal linearly polarized reference system, and obtain

$$A' = \begin{pmatrix} a'_{11} & a'_{12} \\ a'_{21} & a'_{22} \end{pmatrix} \quad , \qquad (31)$$

the same scattering matrix expressed in a system using reference elliptical polarizations h_1 and h_2 . The advantage of choosing orthogonal elliptically polarized reference vectors is that a proper choice makes the scattering matrix real and diagonal. This process is similar to choosing normal coordinates in mechanics.

(4). Maximum and Minimum Echo and Associated Polarizations

Let us study the variation of Q by using a reference system in which the scattering matrix is real and diagonal. Then

$$Q = |\mathrm{h}^r A \mathrm{h}^t| \qquad (32)$$

where

$$A = \begin{pmatrix} a_{11} & 0 \\ 0 & a_{22} \end{pmatrix} \quad . \qquad (33)$$

Now

$$Q = |h_\theta^t h_\theta^r a_{11} + h_\phi^t h_\phi^r a_{22}| \qquad (34)$$

where

$$|h_\theta^t|^2 + |h_\phi^t|^2 = |h_\theta^r|^2 + |h_\phi^r|^2 = 1 \quad . \qquad (35)$$

The maximum value of Q under these conditions is attained for either

$$h_\theta^t = h_\theta^r = 1 \ , \qquad h_\phi^t = h_\phi^r = 0 \qquad (36)$$

or

$$h_\theta^t = h_\theta^r = 0 \ , \qquad h_\phi^t = h_\phi^r = 1 \qquad (37)$$

according to whether $|a_{11}| > |a_{22}|$ or $|a_{22}| > |a_{11}|$. In either case transmitting and receiving antennas are identical for maximum echo, and the returned signal is of the polarization that the transmitting antenna best receives. These properties are independent of the choice of reference vectors. Therefore, if the scattering matrix is expressed in a linearly polarized reference system:

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} , \tag{38}$$

since the returned wave must be of the polarization which the transmitter best receives

$$A\, \mathrm{h}_{opt} = \lambda\, \mathrm{h}^{*}_{opt} \quad . \tag{39}$$

where the asterisk denotes complex conjugate. Then,

$$Q_{max} = |\mathrm{h}_{opt}\, A\, \mathrm{h}_{opt}| = |\lambda|\ |\mathrm{h}_{opt}\, \mathrm{h}^{*}_{opt}| = |\lambda| \quad , \tag{40}$$

and the maximum echo is proportional to $|\lambda|^2$. Taking the complex conjugate of eq. (39)

$$A^{*}\, \mathrm{h}^{*}_{opt} = \lambda^{*}\, \mathrm{h}_{opt} \quad . \tag{41}$$

Combining,

$$\begin{aligned} A^{*} A\, \mathrm{h}_{opt} &= \lambda^{*} \lambda\, \mathrm{h}_{opt} \\ (A^{*} A - |\lambda|^2 I)\, \mathrm{h}_{opt} &= 0 \ . \end{aligned} \tag{42}$$

The optimum h is an eigenvector of $A^{*} A$, and the maximum echo is the larger of the two roots of the secular determinant. Thus

$$2\ |\lambda|^2_{max} = b + \sqrt{b^2 - 4c} \quad , \tag{43}$$

where

$$\begin{aligned} b &= |a_{11}|^2 + |a_{22}|^2 + 2|a_{12}|^2 \\ c &= |a_{11}\, a_{22}|^2 + |a_{12}|^4 + |a_{12}\, a_{11}|^2 + |a_{12}\, a_{22}|^2 - |a_{12}\, (a_{11} + a_{22})|^2 \ . \end{aligned} \tag{44}$$

The optimum polarization is given by

$$\left(\frac{h_\theta}{h_\phi}\right)_{opt} = \frac{a_{11}\, a^{*}_{12} + a_{12}\, a^{*}_{22}}{|a_{11}|^2 + |a_{12}|^2 - |\lambda|^2_{max}} \ . \tag{45}$$

Since the maximum return can always be achieved using the same antenna for transmitting and receiving, optimum performance will be sought in this class of transmitter-receiver choices. The polarizations which yield zero echo return are given by

$$0 = (h_\theta\ h_\phi) \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} h_\theta \\ h_\phi \end{pmatrix} \tag{46}$$

$$0 = h_\theta^2\, a_{11} + 2h_\theta\, h_\phi\, a_{12} + h_\phi^2\, a_{22} \tag{47}$$

$$\frac{h_\theta}{h_\phi} = \frac{-a_{12} \pm\sqrt{a_{12}^2 - a_{11}\, a_{22}}}{a_{11}} \ . \tag{48}$$

With the condition $|h_\theta|^2 + |h_\phi|^2 = 1$, this is sufficient to determine the two choices of transmitter and receiver polarization which yield echo return.

(5). Discrimination When Clutter Is Isotropic

Suppose that a choice of antenna polarizations is desired which will yield zero response to an isotropic target, but a maximum response to a nonisotropic target. In a circularly polarized reference system, an isotropic target has a scattering matrix of the form

$$A = \begin{pmatrix} 0 & a_{12} \\ a_{12} & 0 \end{pmatrix} \ , \tag{49}$$

since a right-hand circularly polarized antenna used for transmitting and receiving develops no terminal voltage when illuminating an isotropic target, nor does a left-hand circularly polarized transmitting-receiving antenna. The returned wave is of the opposite sense to the transmitted: therefore the off-diagonal terms in the scattering matrix are equal and nonzero. The type of transmitter-receiver combinations that yield zero response from such a target are given by

$$0 = (h_1^r\ h_2^r)\begin{pmatrix} 0 & a_{12} \\ a_{12} & 0 \end{pmatrix}\begin{pmatrix} h_1^t \\ h_2^t \end{pmatrix} \ , \tag{50}$$

$$h_1^t\, h_2^r + h_2^t\, h_1^r = 0 \ . \tag{51}$$

Since

$$|h_1^t|^2 + |h_2^t|^2 = |h_1^r|^2 + |h_2^r|^2 = 1 \ , \tag{52}$$

this condition requires

$$\begin{aligned} h_1^r &= -h_1^t \\ h_2^r &= h_2^t \end{aligned} \ . \tag{53}$$

Thus there are an infinite number of combinations of transmitter and receiver polarizations which give zero echo from an isotropic target. We now determine which of these combinations gives maximum echo from a nonisotropic target, with a scattering matrix (in a circularly polarized reference system)

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \ . \tag{54}$$

For the given class of transmitter-receiver combinations

$$Q = \left| (h_1 \; h_2) \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} -h_1 \\ h_2 \end{pmatrix} \right| \tag{55}$$

$$Q = |a_{22} \, h_2^2 - a_{11} \, h_1^2| \quad . \tag{56}$$

The choice of h_1 and h_2 which makes Q a maximum, subject to the condition

$$|h_1|^2 + |h_2|^2 = 1 \quad , \tag{57}$$

is again

$$\begin{aligned} & h_1 = 1 \; , \; h_2 = 0 \\ \text{or} \quad & \\ & h_2 = 1 \; , \; h_1 = 0 \quad , \end{aligned} \tag{58}$$

depending upon whether $|a_{11}| > |a_{22}|$, or $|a_{22}| > |a_{11}|$. The maximum return from an nonisotropic target will be simultaneously achieved with zero from isotropic clutter for either right-hand circularly polarized identical transmitting and receiving antennas, or identical left-hand circularly polarized transmitting and receiving antennas, depending upon the target. Note that these two choices of transmitter-receiver combinations are the only ones in this class for which transmitter and receiver are identical.

b. Analysis of Data

When the scattering matrix for a single aspect of a radar target has been determined, the polarization which yields maximum or zero echo return may be found by methods already discussed in this report. For a range of aspects of one or more targets, however, an over-all optimum polarization is desired. If, for each aspect of a given target, the complete polarization dependence of echo return can be depicted graphically, then the optimum polarization for a range of aspects can be selected by a study of the superimposed charts.

A graphical presentation of the polarization dependence of echo return may be made by the use of a polarization chart, on which each point corresponds to a particular antenna polarization. If the same antenna is used for transmitting and receiving, constant echo curves may be drawn on this chart, along which curves the echo return from a given target remains constant. Several types of polarization charts are available. The q-plane[4] representation of polarization is a desirable one since the space-fixed angle of the major axis of the polarization ellipse as well as its ellipticity are simply related to the coordinates in this plane. If the vector height of an antenna in a circularly polarized reference system is

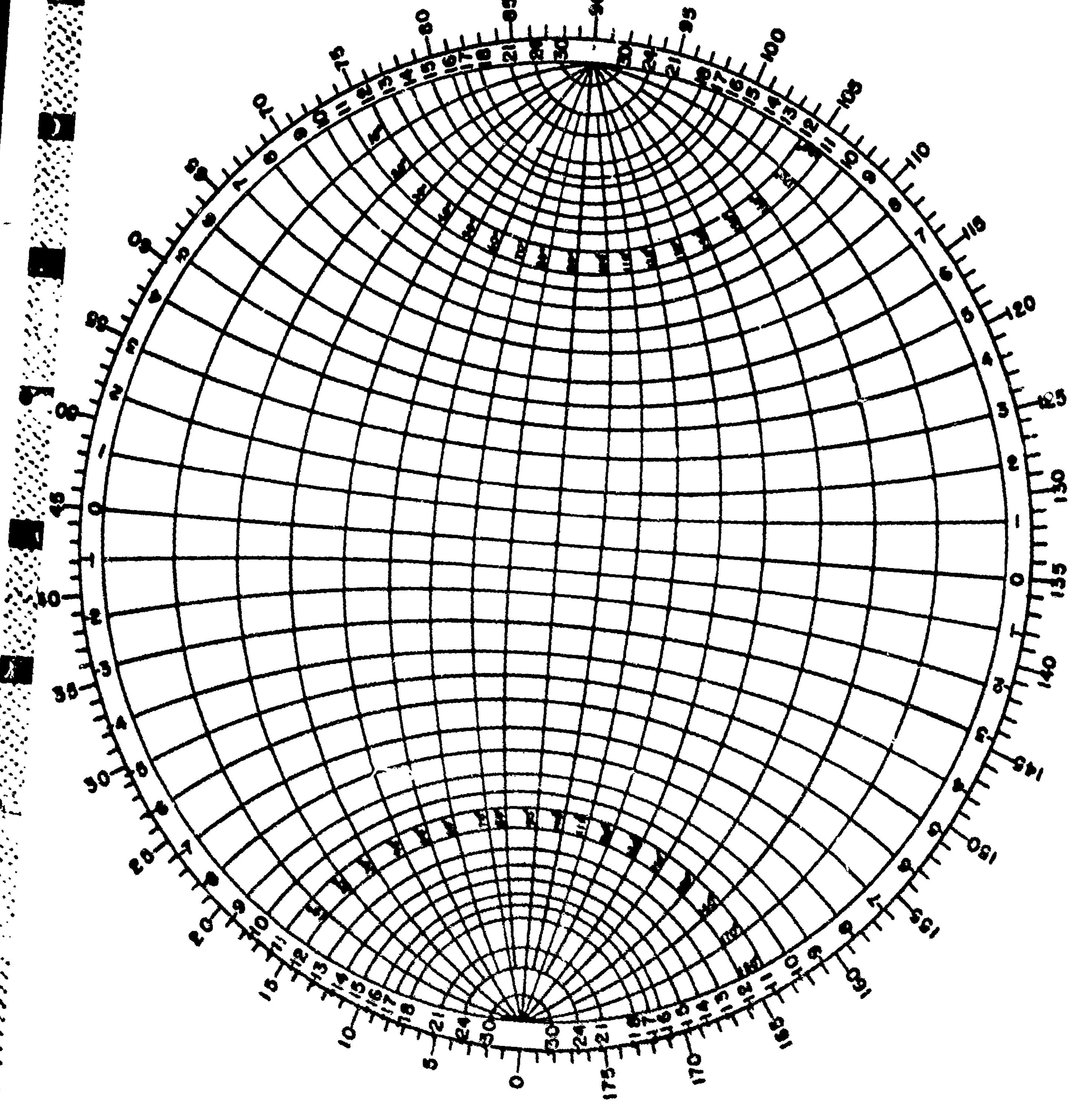


Fig. 2 q-plane polarization chart.

$$h = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \tag{59}$$

then a complex quantity

$$q = \frac{h_1}{h_2} \tag{60}$$

is defined. Plotting these complex points on a plane in the usual manner yields a representation for which each antenna polarization corresponds to a single point. The origin corresponds to circular polarization of one sense; the point at infinity to circular polarization of the other sense. Circles about the origin describe contours of constant $|q|$ along which the ellipticity remains constant, and radial lines describe contours of constant $arg\ q$, along which the space-fixed direction of the major axis remains constant. The ellipticity is given by

$$\epsilon = \left| \frac{1 + |q|}{1 - |q|} \right| \tag{61}$$

and the space-fixed direction of the major axis is an angle ϕ from the reference axis where

$$2\phi = arg\ q \quad . \tag{62}$$

Since the region outside the unit circle in this representation contains all the polarizations of one sense, and the region interior to the unit circle contains all those of the opposite sense, it is found useful to transform the region exterior to the unit circle into the unit circle so that the same representation is obtained for left-handed polarizations as for right-handed polarizations. The q-plane upon which polarizations are plotted consists of two faces of the unit circle. The region corresponding to right-handed elliptical polarizations is one face, the region corresponding to left-handed elliptical polarizations is the other face, and coordinate lines are the same on each face. Such a chart is shown in Fig. 2. The curves along which the echo return for a sample target is a constant number of decibels below the maximum, are plotted on the right and left-hand faces of a q-plane chart to illustrate this variation in Figs. 3 and 4. The q-plane representation has the disadvantage (as do all plane representations of polarization) of distorting the true distance between points on the polarization chart, and the constant echo curves are also seen to be quite complicated. For another choice of reference polarizations, other than circularly polarized, another chart of this type could be constructed; the distance between two points on the chart differing from that obtained in the q-plane representation. The choice of base vectors which will best simplify the constant echo curves would be that choice for which the scattering matrix becomes diagonal. A better picture of the true form of the constant echo curves is obtained by the use of a three-dimensional polarization chart.

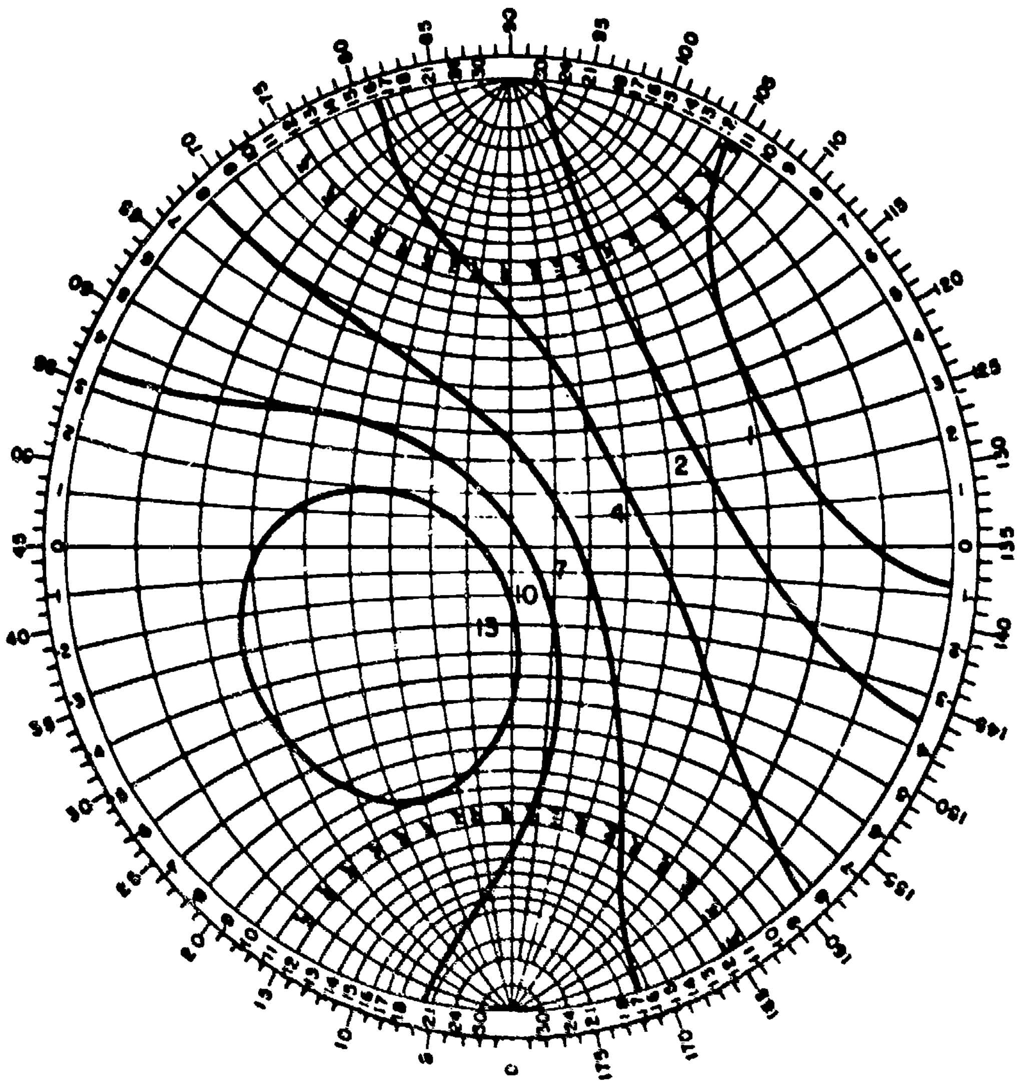


Fig. 3 Constant echo loci on polarization chart (right-handed).

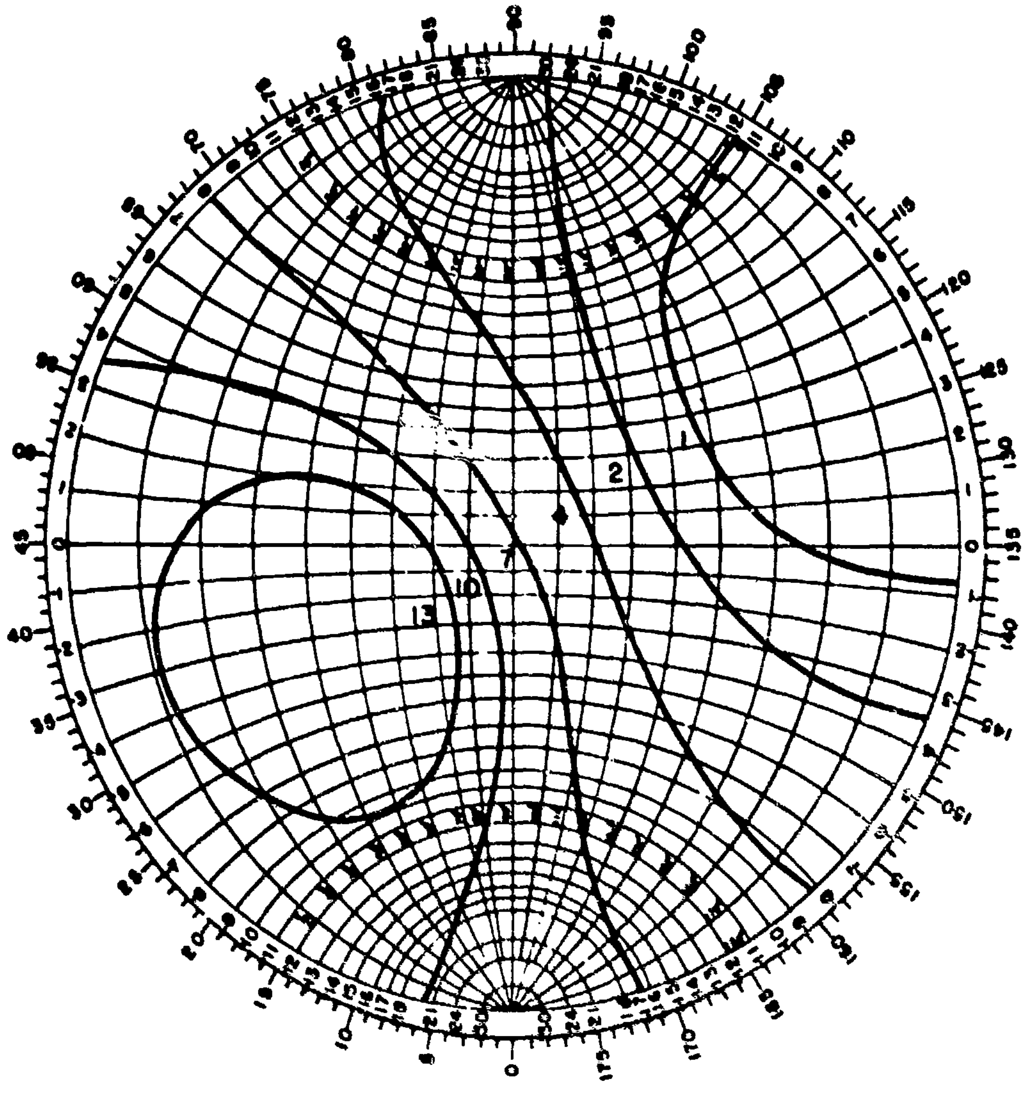


Fig. 4 Constant echo loci on polarization chart (left-handed).

When proper base vectors are chosen, the scattering matrix becomes real and diagonal, and

$$Q^2 = \left| (h_1\ h_2) \begin{pmatrix} a_{11} & 0 \\ 0 & a_{22} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \right|^2 \tag{63}$$

$$Q^2 = \left| a_{11}\ h_1^2 + a_{22}\ h_2^2 \right|^2 \tag{64}$$

where h_1 and h_2 are the complex components of the vector antenna height in this elliptically polarized reference system.

$$\begin{aligned} h_1 &= H_1\ e^{j\ \delta/2} \\ h_2 &= H_2\ e^{-j\ \delta/2} \end{aligned} \tag{65}$$

where H_1 and H_2 are real and positive, and δ is the phase lead of h_1 over h_2 . A three-component vector P is now defined for each polarization h_1 , h_2 by the relations.

$$\mathrm{P} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{66}$$

$$\begin{aligned} x &= \frac{H_1^2 - H_2^2}{2} \\ y &= H_1\ H_2\ \cos\delta \\ z &= H_1\ H_2\ \sin\delta \quad . \end{aligned} \tag{67}$$

Then, since

$$H_1^2 + H_2^2 = 1 \tag{68}$$

$$x^2 + y^2 + z^2 = \frac{H_1^4}{4} + \frac{H_2^4}{4} - \frac{H_1^2\ H_2^2}{2} + H_1^2\ H_2^2 = \left(\frac{H_1^2 + H_2^2}{2}\right)^2 = \frac{1}{4} \quad . \tag{69}$$

The vector P is restricted to a sphere of radius $r = ½$. To each point on the sphere corresponds one and only one elliptical polarization. Now

$$Q^2 = \left| a_{11}\ h_1^2 + a_{22}\ h_2^2 \right|^2 \tag{70}$$

$$Q^2 = a_{11}^2\ H_1^4 + a_{22}^2\ H_2^4 + 2a_{11}\ a_{22}\ H_1^2\ H_2^2\ \cos 2\delta \tag{71}$$

$$Q^2 = a_{11}^2\ (x + ½)^2 + a_{22}^2\ (x - ½)^2 + 2a_{11}\ a_{22}\ (y^2 - z^2)\ . \tag{72}$$

The condition Q^2 = constant fixes the echo return, and limits the vector P to lie on a quadric surface given by

$$C^2 = a_{11}^2 \, (x + \tfrac{1}{2})^2 + a_{22}^2 \, (x - \tfrac{1}{2})^2 + 2a_{11} \, a_{22} \, (y^2 - z^2) \; . \tag{73}$$

But since P must also lie on a sphere of radius ½ . we are interested in the intersections of this quadric surface with the sphere. If the curves on the surface of the sphere were projected upon the xy-plane. the z-dependence would vanish. The equation of this projected curve may be obtained by eliminating z from

$$C^2 = a_{11}^2 \, (x + \tfrac{1}{2})^2 + a_{22}^2 \, (x - \tfrac{1}{2})^2 + 2a_{11} \, a_{22} \, (y^2 - z^2) \tag{74}$$

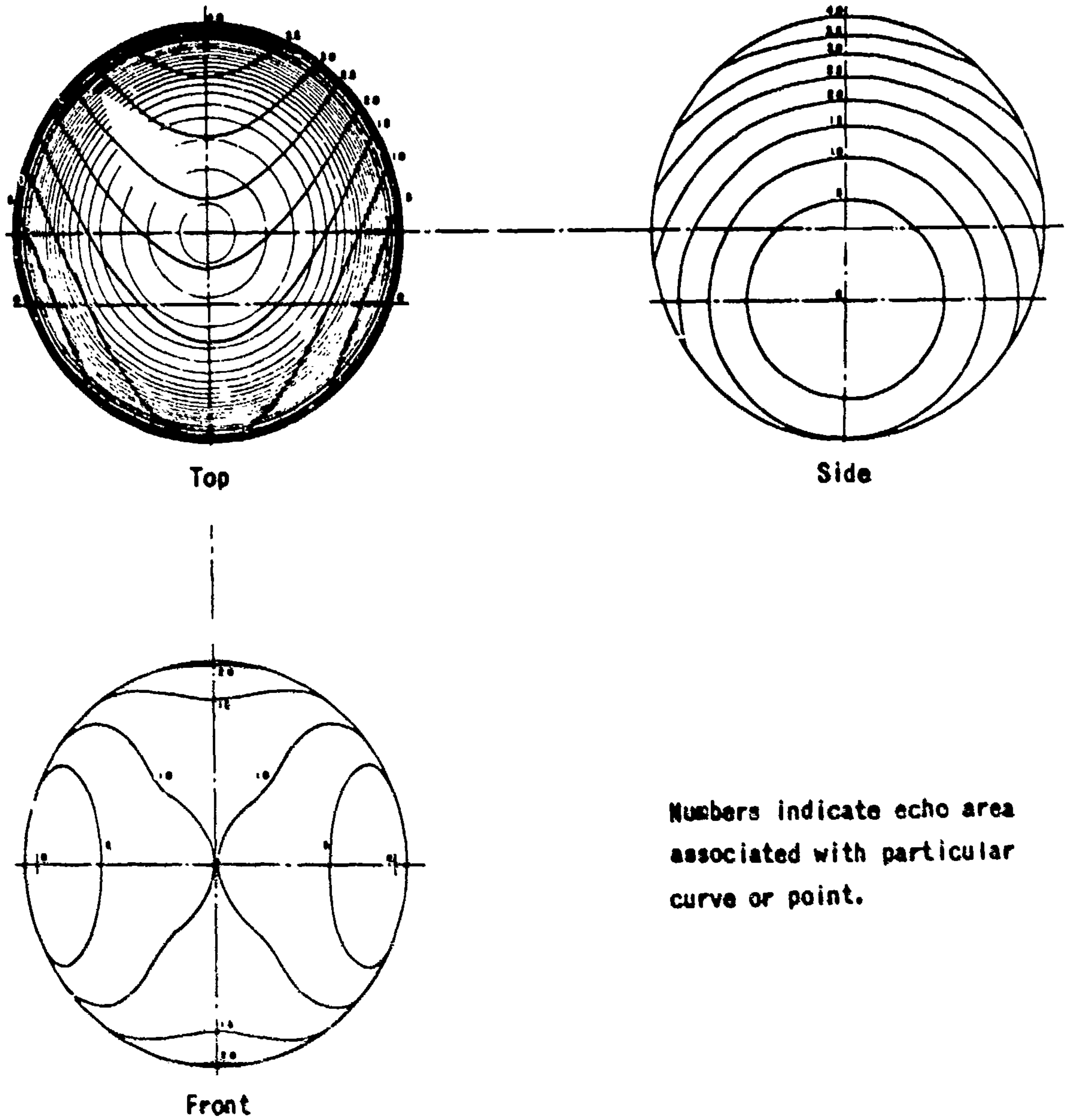
$$x^2 + y^2 + z^2 = \frac{1}{4} \; . \tag{75}$$

or

$$\begin{aligned} C^2 &= (a_{11} + a_{22})^2 \, (x - d)^2 + 4a_{11} \, a_{22} \, y^2 \\ d &= \frac{1}{2} \left(\frac{a_{11} - a_{22}}{a_{11} + a_{22}} \right) \; . \end{aligned} \tag{76}$$

This is the equation of an ellipse with center at $x = d$ $y = 0$. The projections of the constant echo curves on the xy-plane are, therefore, a family of concentric ellipses with the same eccentricity. The orthographic projections to the three principal planes of the constant echo curves on the polarization sphere are shown in Fig. 5. Top view corresponds to looking along the y axis at the sphere front view is looking along the x-axis, and side view is taken along the z axis. The polarization sphere is not a new concept,[5] and has the advantage of being an undistorted representation of polarization. The q-plane method of representing polarization is simply a polar projection of the points on the surface of the sphere using two opposite poles of the sphere corresponding to the choice of reference polarizations. In particular the q plane chart we have discussed uses right and left-handed circularly polarized pole points If that projection were made of the curves illustrated in Fig. 5 since the poles might be arbitrarily located on the sphere with reference to the optimum coordinate axes a complicated set of curves would be obtained However from a knowledge of the constant echo loci on the sphere their projection in a preferred set of directions can always be visualized. Comparison of the constant echo curves for more than one target may be made on the surface of the sphere itself and the projection which causes least distortion of areas of interest can be chosen.

Several general classifications of radar targets are suggested by the form of the constant echo curves on the polarization sphere The curves for a given target are seen to depend only upon the separation of the two polarizations which



Numbers indicate echo area associated with particular curve or point.

Fig. 5 Constant echo loci on polarization sphere.

yield zero return, and the location of these two points on the polarization sphere. If the two points on the sphere for which zero echo is obtained coincide, the constant echo curves are circles on the surface of the sphere, and maximum echo is achieved for the polarization orthogonal to that yielding zero echo, represented by the diametrically opposite point. A target such as this, for which only one choice of antenna polarization yields zero echo return, could be called a ''linear'' target. A wire is a particular case of linear target. A ''linear'' target always returns a wave of a given elliptical polarization, regardless of transmitter polarization.

If the two polarizations for which zero echo is obtained are a maximum distance apart (opposite poles) the constant echo loci are again circles on the polarization sphere, and maximum echo is obtained for any point on the equator relative to the two poles. Such a target may be called a generalized ''isotropic'' target. A sphere is a particular case of an isotropic target for which the two poles of zero return are the circularly polarized poles of the polarization sphere. A general target would be one for which the polarizations of zero return are located at some distance intermediate to zero and the diameter of the polarization sphere.

c. Measurement of Scattering Matrix

(1). Variation of Scattering Matrix With Coordinate Rotation

In the determination of the components of the scattering matrix by amplitude measurements alone, the effect of coordinate rotations on those components is important.

If the scattering matrix (for linearly polarized reference vectors) relative to the unprimed coordinate system shown in Fig. 6 is

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} . \tag{77}$$

and the coordinate axes defining the positive θ and ϕ directions are rotated by an angle ϕ about the z-axis to the directions indicated by the primed vectors, the components of the incident and reflected waves relative to this new coordinate system transform according to:

$$\begin{aligned} E_\theta &= \cos\phi\, E_\theta' - \sin\phi\, E_\phi' \\ E_\phi &= \sin\phi\, E_\theta' + \cos\phi\, E_\phi' \end{aligned} \tag{78}$$

where the unprimed components refer to the original axes and the primed components to the new axes. The vector height of transmitting and receiving antennas transform in

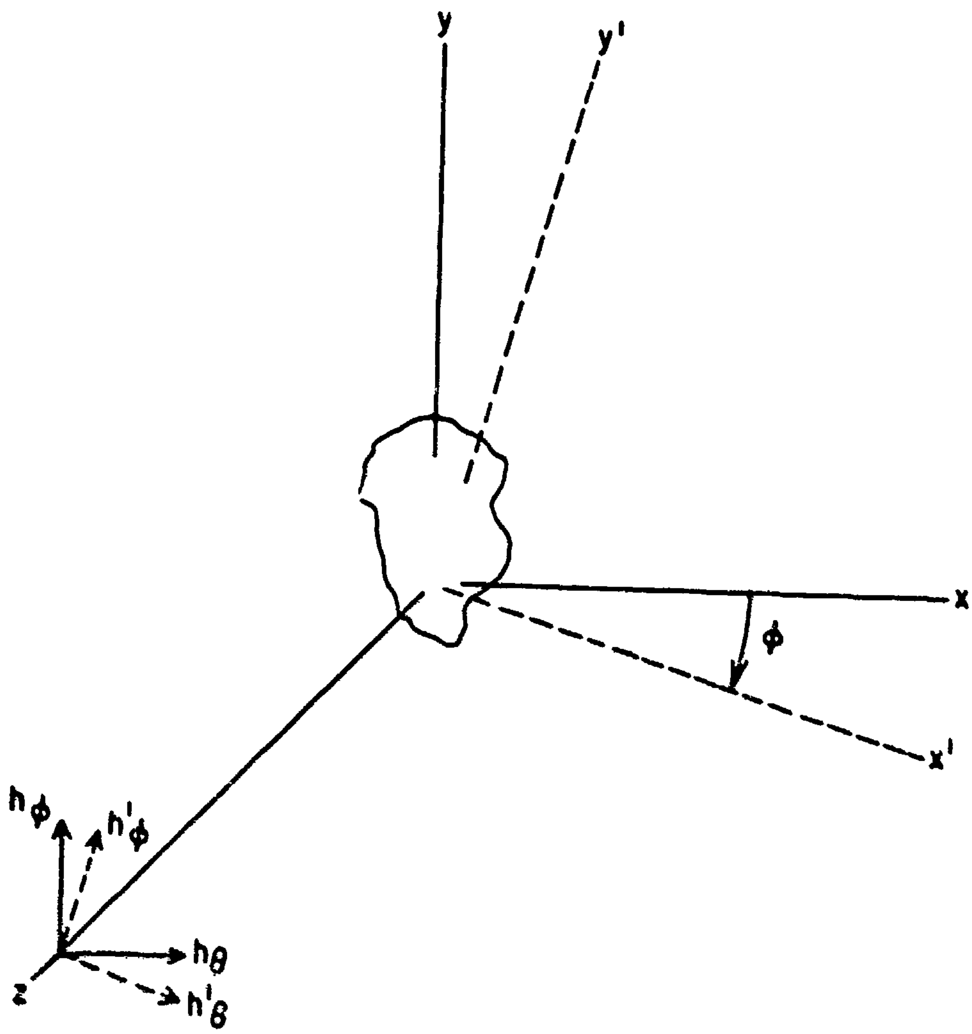


Fig. 6 Coordinate rotations.

the same manner; hence

$$Q = \left| (h_\theta \; h_\phi) \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} h_\theta \\ h_\phi \end{pmatrix} \right| \tag{79}$$

$$Q = \left| (h'_\theta \; h'_\phi) \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} h'_\theta \\ h'_\phi \end{pmatrix} \right| \tag{80}$$

$$Q = \left| (h'_\theta \; h'_\phi) \begin{pmatrix} a'_{11} & a'_{12} \\ a'_{21} & a'_{22} \end{pmatrix} \begin{pmatrix} h'_\theta \\ h'_\phi \end{pmatrix} \right| \tag{81}$$

where

$$\begin{aligned} a'_{11} &= a_{11} \cos^2\phi + 2a_{12} \sin\phi\cos\phi + a_{22} \sin^2\phi \\ a'_{21} = a'_{12} &= (a_{22} - a_{11}) \sin\phi\cos\phi + a_{12} (\cos^2\phi - \sin^2\phi) \\ a'_{22} &= a_{11} \sin^2\phi - 2a_{12} \sin\phi\cos\phi + a_{22} \cos^2\phi \; . \end{aligned} \tag{82}$$

These equations relate the components of the scattering matrix (for linearly polarized reference vectors) relative to one coordinate system to those in a coordinate system rotated a positive angle ϕ about the z-axis. If the same linearly polarized antenna is used for transmitting and receiving, the equation for a'_{11} describes the variation in received voltage as the antenna is rotated about the z-axis. If a linearly polarized transmitting antenna and an orthogonal linearly polarized receiving antenna are both rotated about the z-axis, the equation for a'_{12} describes the variation in received voltage as a function of the angle of rotation. The equation for a'_{22} is the same as that for a'_{11}, with ϕ replaced by $\phi + \pi/2$.

The determination of the components of the scattering matrix involves the determination of three magnitudes and two relative phases. Seven amplitude measurements are necessary to completely determine the scattering matrix.

From the equation

$$a'_{12}(\phi) = \frac{(a_{22} - a_{11})}{2} \sin 2\phi + a_{12} \cos 2\phi \tag{83}$$

$$a'_{12}(0^\circ) = a_{12} \tag{84}$$

$$a'_{12}(45^\circ) = \frac{a_{22} - a_{11}}{2} \tag{85}$$

$$a'_{12}\ (22.5^{\circ}) = \frac{\sqrt{2}}{2}\left(\frac{a_{22} - a_{11}}{2} + a_{12}\right) \quad . \tag{86}$$

The absolute magnitudes of these three complex quantities can be measured using a vertically polarized transmitting antenna and a horizontally polarized receiving antenna in each of the three reference positions. A vector triangle may be constructed, as in Fig. 7a, to find the relative phases of the complex quantities. An ambiguity in the sign of the phase angle of a_{12} relative to $a_{22} - a_{11}$ arises. The phase of a_{12} relative to $a_{11} - a_{22}$ is either $+\alpha$ or $-\alpha$, depending upon whether the vector triangle is the triangle with solid sides, or the one with dotted sides. A measurement of the magnitude of the voltage received when using a circularly polarized transmitting-receiving antenna combination yields the magnitude of the vector

$$\frac{a_{11} - a_{22}}{2} + j\ a_{12} \quad . \tag{87}$$

Only one choice of phase for a_{12} will yield this magnitude; hence the phase of a_{12} relative to $a_{11} - a_{22}$ is determined. Let the two vectors a_{12} and $a_{11} - a_{22}$ be represented in Fig. 7b. Measurement of the absolute magnitudes of the quantities

$$\begin{aligned} a'_{11}\ (0^{\circ}) &= a_{11} \\ a'_{22}\ (0^{\circ}) &= a_{22} \end{aligned} \tag{88}$$

may be made using the same linearly polarized antenna for transmitting and receiving. The vector triangle with sides a_{11}, a_{22}, and $a_{11} - a_{22}$ may be constructed, with an ambiguity in the sign of the phase angles β and γ of a_{11} and a_{22} respectively relative to the reference vector $a_{11} - a_{22}$, as shown in Fig. 7c. A measurement of the magnitude of $a'_{11}\ (45^{\circ})$ will determine which vector triangle is correct, since only one will give the correct value for $a'_{11}\ (45^{\circ})$ from the formula

$$a'_{11}\ (45^{\circ}) = \frac{1}{2}\,(a_{11} + a_{22} - 2a_{12}) \quad . \tag{89}$$

Thus the magnitudes and relative phases of the components of the scattering matrix can be determined from seven amplitude measurements alone.

d. Experimental Studies

(1). Introduction

The experimental work on this project has been done primarily in the second half of the contract year. Because of the nature of the original contract it was considered only a minor extension of the principal purposes of the contract, namely, theoretical predictions and analysis of techniques to be used in various a.

b.

c.

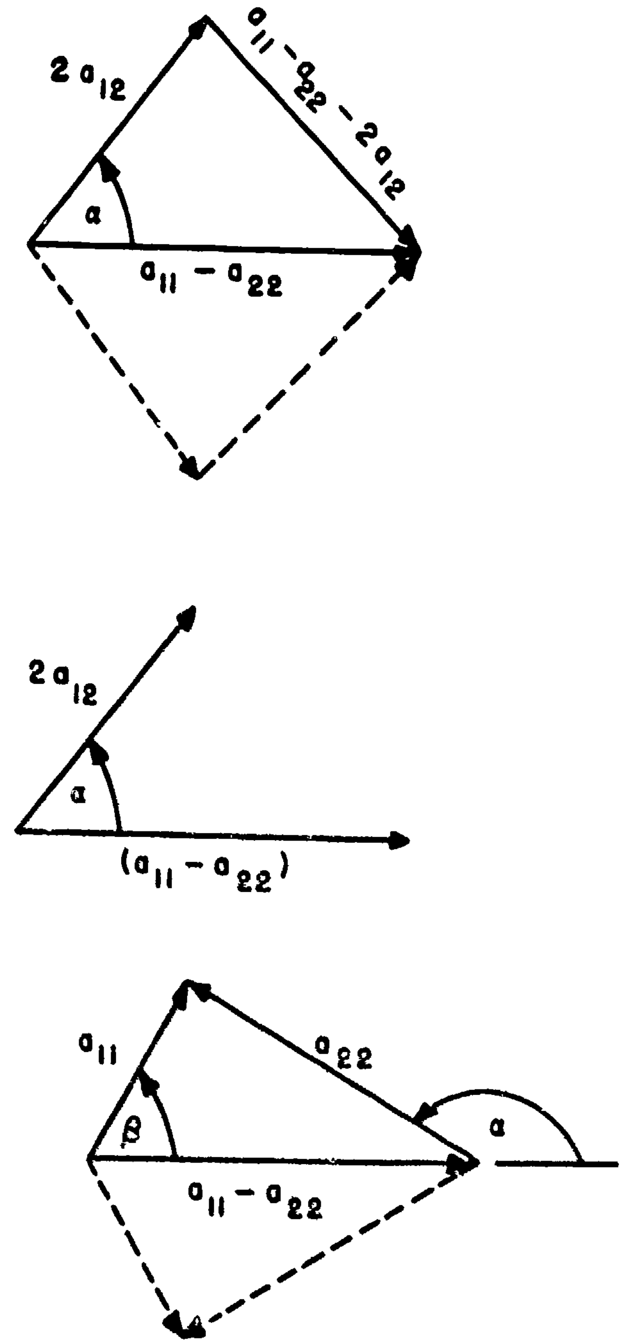


Fig. 7 Vector triangle resolution.

polarization studies. It was desired, however, to develop special equipment which could be used to test the validity and usefulness of the theoretical studies and to obtain additional polarization data from actual reflection measurements. It was necessary to develop apparatus with which to measure the scattering matrix of a given target for all aspects.

The basic problem of polarization reflection measurements is to devise a system which transmits waves of arbitrary polarization and is simultaneously capable of measuring the return echo, which may again be of arbitrary polarization.

Scattering matrices can be determined from measurements made with linearly polarized transmitted waves. Since techniques for measuring the ordinary component of echo are well developed, the major effort has been devoted to developing equipment to measure the cross polarized component of echo.

(2). The Measuring Apparatus

Construction of S- and X-band signal generating equipment, to be used for proposed polarization reflection studies, is underway. This equipment employs conventional tubes as frequency multipliers which drive Sperry klystrons to provide crystal-controlled, 1000-cycle modulated output at S- and X-bands. The output is designed to be extremely stable with respect to frequency, power, and modulation variations.

Complete descriptions of this generating equipment are available in Project Report 302-28.[7] It contains electrical diagrams of the system together with a discussion of the design features and capabilities of each component. The following are the only important design changes:

(a). Instead of a wave analyzer (as shown in Fig. 1 of Project Report 302-28) with output at 50 kilocycles, a highly selective 1000-cycle amplifier, designed at the Antenna Laboratory, is used. The response of the amplifier is four cycles wide at the half-power points.

(b). In place of the standard audio generator (located at a central point in the laboratory) a 1000-cycle tuning fork source is built into the equipment.

(c). A linear amplifier is included on the same chassis with the square root amplifier, rather than on a separate chassis.

Other than the above changes, the generating equipment is essentially as described.

The first equipment for the proposed polarization measurements was designed as follows. A variation on a hybrid (or magic) T was built with the two colinear arms made of one-inch square wave guide. The E- and H-plane arms, corresponding to those of a conventional hybrid T were made of 1 by ½-inch wave guide. A second 1 by ½-inch E-plane arm was placed directly opposite the H-plane arm on the square wave guide. This apparatus was a form of what may be call a ''hybrid X'' and was designed to permit simultaneous reception of both the ordinary and cross polarized components of the return signal.

The hybrid X system, briefly described above, was only partially successful. Its principal disadvantage was the great amount of cross coupling between the two orthogonally polarized receiving arms. This cross coupling was due to the fact that the two receiving arms were located at the same junction and were not perfectly matched to the square section forming the colinear arms of the hybrid T. The matching could undoubtedly have been improved by the addition of triple stub tuners in each of the two arms. It was believed, however, that this would introduce other complicating factors into the operation of the arms. The two receiving arms are shown in Fig. 8. They are designed for superheterodyne detection with an intermediate frequency of 30 mc; hence efficient mixing action is highly important.

Even though tests showed the two arms responded primarily to linear components of the return wave separated by 90°, there was still sufficient distortion of the fields at the common junction(and reflections at the mouth of each arm)to greatly decrease the effective isolation between the two arms.

A second difficulty concerned nulling techniques. The basic problem of nulling is to design the receiving system to obtain a high degree of discrimination against the outgoing wave in favor of the incoming or reflected one. When this discrimination has been achieved the receiver is said to be nulled. In the hybrid X system the nulling probes, which consisted of two sets of three probes each, were not completely independent of each other; for even though the two sets of probes were mounted in perpendicular planes in the square guide, there still was interaction between the two sets. Consequently, the adjustments of the probes to null the ordinary receiving arm upset the nulling of the cross polarized receiving arm and vice versa. These inherent difficulties of the hybrid X system indicated certain desirable changes in design.

The present measuring assembly, exclusive of all signal generating equipment, is shown in Fig. 8. It was developed from considerations of the disadvantages of the hybrid X system. It was desired to obtain a system in which the two orthogonally polarized receiving arms are more independent of each other, that is,

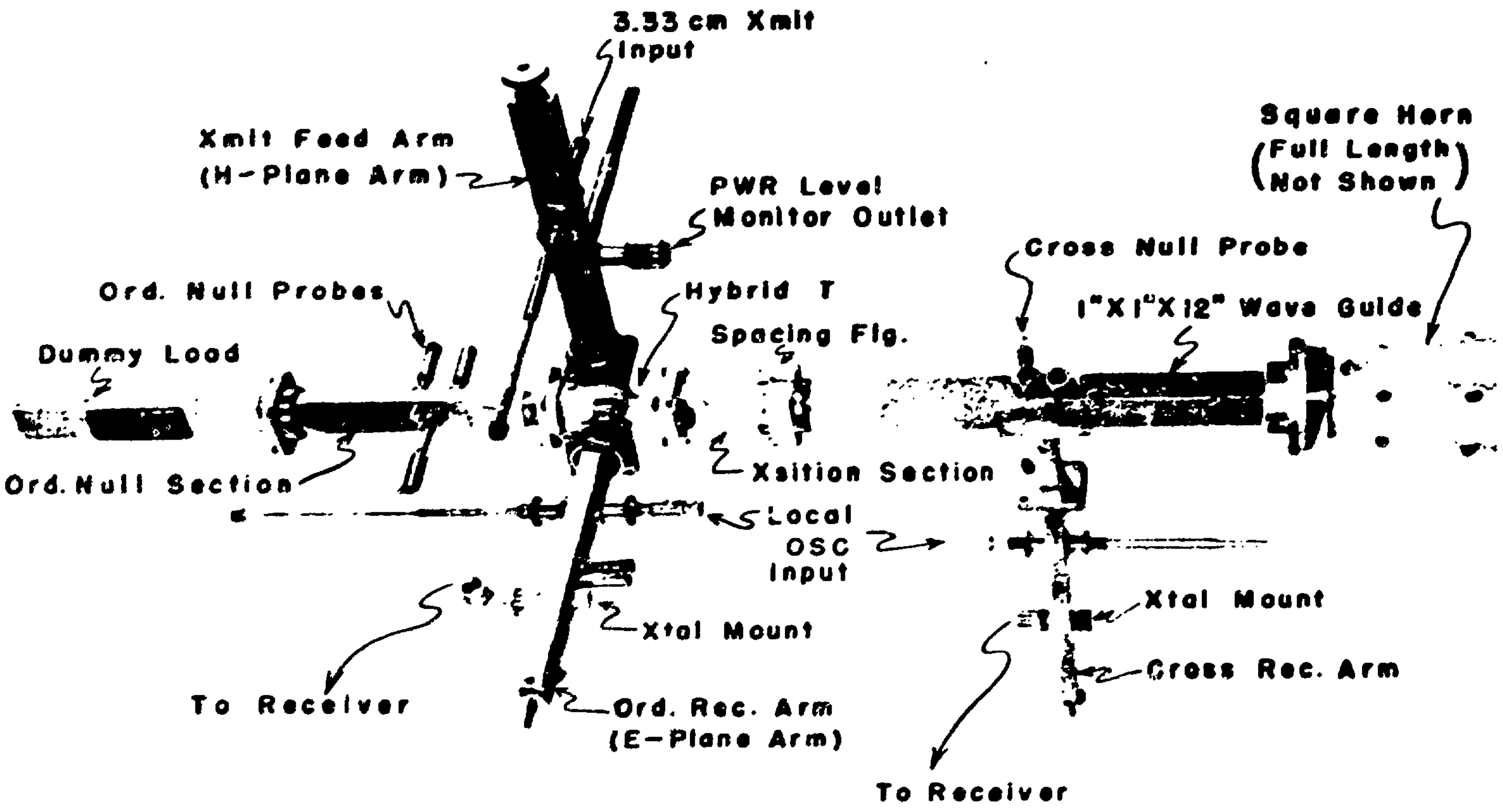


Fig. 8 Measuring assembly.

respond only to their respective polarizations with little or no cross coupling. To accomplish this the two receiving arms are effectively isolated by leaving the ordinary receiving arm as the E-plane arm of a hybrid T, and placing the cross polarized receiving arm on the side of a 12-inch length of one-inch square wave guide. This square section of guide is then connected to the output colinear arm of the hybrid T by a tapered transition section as shown in Fig. 9. The tapered transition section acts as a wave guide filter for the cross polarized component of the return signal; hence the two arms are effectively isolated as far as cross coupling is concerned, provided rotation of the plane of the cross polarized component, while passing through the square section and the transition section, is held to a low value. If symmetry is maintained, only the ordinary component passes through the transition section to the hybrid T.

While this method seemed an adequate solution to the first difficulty of the hybrid system, that is, cross coupling between the two arms, it appeared likely to increase the difficulties of obtaining simultaneous nulls in both receiving arms; hence the problem of nulling the cross polarized receiving arm was considered in some detail. The use of a phasing line and attenuator system was considered to introduce a signal from the source into the cross polarized arm. If the signal is of the proper phase and amplitude, it will cancel the residual signal picked up by that arm from the transmitted wave. The residual signal would be produced by the almost unavoidable rotation of the transmitted E vector in passing through the transition and square guide sections. It would be a complicated system of nulling, however, and subject to problems of vibration effects and operating stability.

In order to obtain a more simple and stable null, a small probe was inserted at a point along the side of the square guide section at the proper position, depth, and angle to couple a signal of the required phase and amplitude into the cross polarized arm to cancel the residual signal in that arm. Thus with no target in place the resultant signal into the cross polarized arm was very nearly zero, which satisfied the required condition for a useable null. The cross polarized null was adjusted first, and then movement of the ordinary nulling probes had little effect on the cross polarized null due to the isolation provided by the tapered transition section.

The transmitter input source consists of a 3.33-cm crystal-controlled output of several milliwatts square-wave modulated at a frequency of 1000 cps. Referring to Fig. 8, the usual procedure is to feed the transmitter input with the E-plane horizontal into the H-plane arm of the hybrid T. The load arm of the T is connected to the ordinary nulling section which consists of three metal probes 1/16-inch in diameter protruding into the guide parallel to the E vector. These probes are

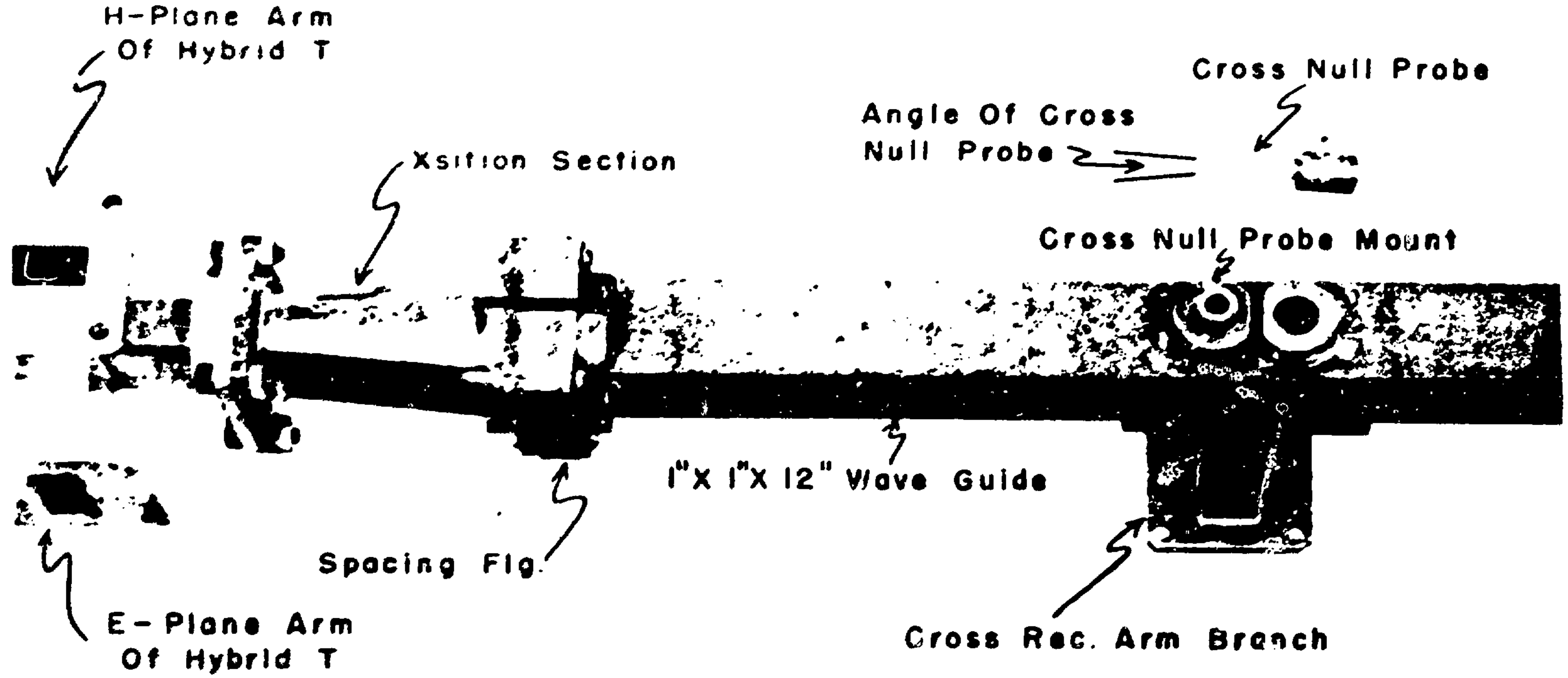


Fig. 9 Detail of cross polarized receiving section.

screwed into the guide using extremely fine threads.

The ordinary nulling section connects to a commercial, attenuator-card-type, dummy load. Approximately one-half of the input power is absorbed in the dummy load. The remaining half of the input power passes through the transition section into the 12-inch square guide section and thence to a square horn.

A short piece of rectangular (1 by ½-inch) wave guide branches off the middle of the square guide section and receives the cross polarized component of the return signal. The nulling probe, inserted vertically through the wall of the square guide opposite the rectangular cross polarized arm, is shown in Fig. 9. This probe is a short piece of No. 22 copper wire embedded in a 1½-inch length of 1/8-inch diameter polystyrene rod. The piece of wire embedded in the rod protrudes about 7/32-inch into the square guide without touching the wall of the guide. The nulling depth and angle are determined experimentally. When adjusted properly the probe gives a very satisfactory null in the cross polarized arm. After the cross polarized arm is nulled,the nulling of the ordinary receiving arm (still with no target in place) is accomplished with the three metal probes in the ordinary nulling section. As mentioned previously this adjustment does not affect the cross polarized null, but the converse is not true. Thus by several very careful adjustments it is possible to achieve nulls in both receiving arms simultaneously with full power output.

It has been found desirable when making measurements to transmit horizontal polarization to minimize reflections from the ground. The horn used is 17 wavelengths long with a total flare angle of 11°. With this horn difficulties were encountered from multiple reflections due primarily to the presence of minor lobes in the E-plane pattern. Operating with the target at a short range and transmitting a horizontally polarized wave, the effects of multiple reflections were decreased but not completely eliminated.

The effects of multiple reflections were observed by using metal spheres ranging from three to eight inches in diameter as targets,and noting the variations in amplitude of the return signal as the spheres oscillated slowly in a horizontal plane. Large percentage variations were observed in the return to the ordinary receiving arm. These variations were much larger than those which would have resulted if only the effect of the varying range were present. In order to minimize these effects and increase the reliability of the measurements obtained with the system especially with large models and extended targets such as rain, a new horn has recently been completed which has a sharper beam, larger aperture, and no minor lobes of any importance in either the E- or H-planes. This horn is 55 wavelengths long with a total flare angle of 11°. A test of this horn showed that the variations in the amplitudes of the return signals from several spheres due to small motions were not greater than plus or minus three per cent.

(3). Tests of the Measuring Assembly

The following results have been obtained in determining the over-all response of the measuring assembly.

(a). A straight thin wire gives maximum return in the ordinary polarized receiving arm when the wire is oriented parallel to the transmitted E vector. The return signal in the ordinary receiving arm decreases at least 35 db as the wire is rotated 90° in a plane perpendicular to the direction of propagation.

(b). A thin wire at 45° to the vertical gives maximum return in the cross polarized receiving arm. A vertical or horizontal wire gives noise level response (at least 30 db down) in the same receiving arm.

(c). A thin wire at 45° to the vertical gives comparable return in both the ordinary and cross polarized receiving arms.

(d). The return in the ordinary polarized arm from a metal sphere is large while the return in the cross polarized arm from the same sphere is at least 35 db down, as it should be.

(e). Crudely simulated rainfall gives a large return in the ordinary arm. The same simulated rainfall gives return more than 40 db down in the cross polarized arm.

(f). The sensitivity of the system is sufficient to record the effects of single drops and small metal balls 3/16-inch in diameter as they fall through the beam approximately 10 feet from the mouth of the horn. The return from the single drops or the small balls is observable only when using the ordinary polarized arm. No return is indicated from these in the cross polarized arm

(g). Preliminary tests using a model of the F-80 (1/20 scale) with the wings horizontal, and transmitting a vertically polarized wave, indicate large fluctuations in the return to the cross polarized arm as the model is rotated about a vertical axis. The variation between the maximum broadside return signal and the return signal when the nose or tail is head-on is more than 40 db.

Further details of the above tests are:

(a). This measurement was made using a vertically polarized transmitted signal. As in all these tests, the apparatus was first nulled properly in both receiving arms. A 6-inch wire, 1/16-inch in diameter, was suspended vertically, and the amplitude of the ordinary polarized component returned from the wire was observed on the speedomax recorder. The wire was then rotated 90° in a plane perpendicular to the direction of propagation and a second reading made.

(b). In this measurement a horizontally polarized wave was transmitted. The same thin wire used in (a). was placed at an angle of 45° to the vertical and rotated about a vertical axis until peak return was indicated. The wire was then rotated about the direction of propagation in steps of 5° or 10° (measured with a transit) and the amplitude of the return signal in the cross polarized arm was measured and plotted, as shown in Fig. 10.

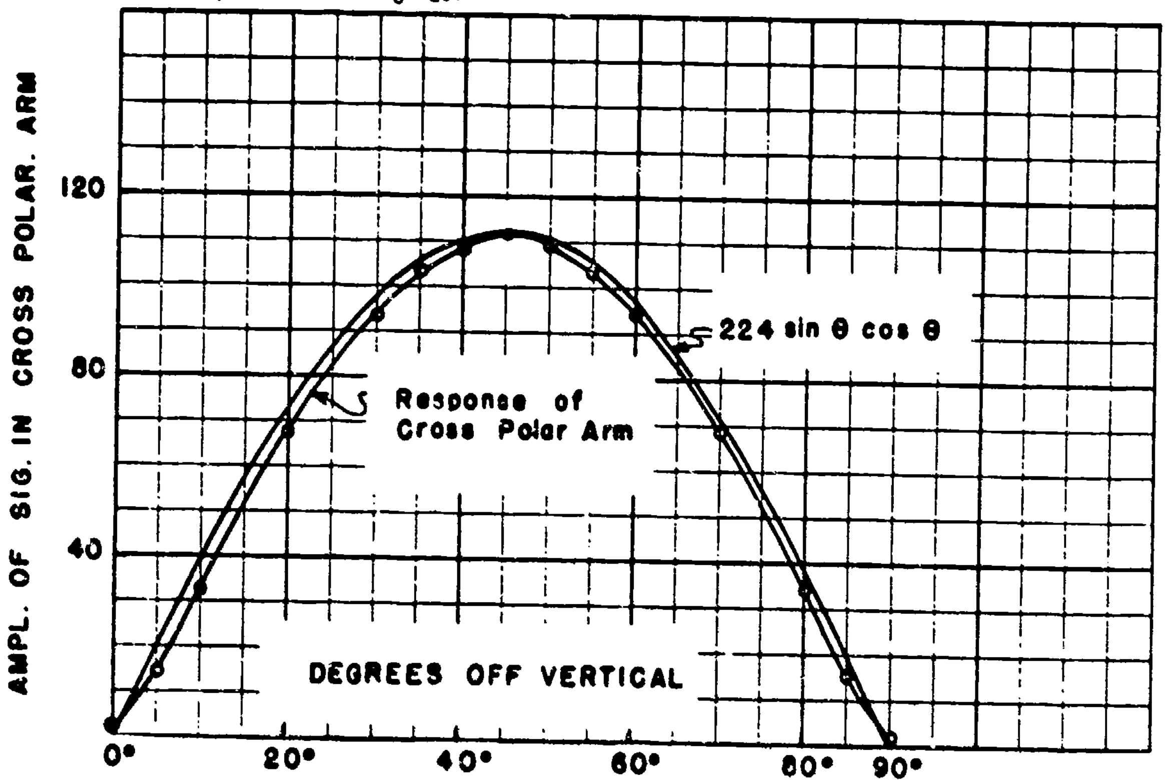


Fig. 10 Comparison of response curve of cross polarization arm with theoretical $A_o \sin\theta \cos\theta$ curve.

The two curves shown in the figure are normalized to have a common point at $\theta = 45°$; for successive points were obtained by rotating the wire through known angles on both sides of 45°. Further calibration work must be done, however, before a curve such as this can be used as a standard for the characteristics of the cross polarized arm; for an accurate calibration of the receiver at the gain setting used is not available. The curve is included primarily to show the general shape of the response curve of the cross polarized arm in comparison with the ideal $\sin\theta \cos\theta$ relation.

(c). To obtain this measurement the same wire was again placed at an angle of 45° with the vertical. When transmitting either horizontal or vertical polarization, the return should be of the same amplitude in both arms. This ideal condition has not yet been obtained due to a small mismatch between the cross polarized arm and the square guide section, which causes the sensitivity of this arm to be six db down with respect to the ordinary arm when using the small horn, and 14 db down when using the newer horn, on which matching adjustments have not been completed. Since these differences in sensitivities between the two arms are constant during any set of measurements, the necessary compensations can be made in the gain of the receiving equipment to give equal speedomax readings in both arms with the wire at 45°. It is expected that matching adjustments can be made when using the new square horn which will bring the differences in sensitivities within six db or less.

(d). The 35-db figure given here is the lower limit of the isolation between the two receiving arms. It has not been possible, thus far, to measure the upper limit with a useful degree of accuracy. The measurement of the lower limit of isolation was made by using a five-inch metal sphere and measuring the ratio of the return signal from the sphere in the ordinary arm to that in the cross polarized arm. The return signal in the cross polarized arm was undetectable and taken as noise level. The six-db difference in the sensitivities of the two arms was taken into account to obtain the figure of 35 db. To obtain the upper limit of isolation between the two arms it will be necessary to use a target with a back scattering matrix like a sphere, and with an extremely large echo area (perhaps a large metal disc), before a detectable response will be obtained in the cross polarized arm.

The above measurement was confirmed by an alternative method. Using a 10-inch metal sphere, noise level response was indicated in the cross polarized arm, and the speedomax reading of the noise level was noted. Leaving the sphere in place, the receiver was changed to the ordinary arm, and the necessary attenuation inserted to give the same reading on the speedomax. The attenuation inserted was 38 db in the audio line and approximately 18 db in the intermediate frequency section of the APR-4 receiver. Subtracting the six-db difference between the sensitivities of the two receiving arms yields an isolation figure of approximately 50 db. This is a good check of the isolation figure of 35 db given previously, and it also indicates that 35 db may be too conservative.

(e). Rainfall was simulated by using overhead hoses and showerheads, with the drops falling approximately 9 to 14 feet before reaching the center of the beam. Due to varying wind conditions there was a large variety of shapes and sizes of drops. Nevertheless, this simulated rainfall gave return in the cross polarized arm that was more than 40 db down from the return in the ordinary polarized arm.

(f). and (g). There are no further details at present to add to these two sections.

It should be pointed out that all measurements to date have been carried out with borrowed equipment, and under these conditions it is not possible to state the exact quantitative accuracy of the measurements included herein. In all cases conservative values have been given.

D. CONCLUSIONS

No advantage is to be gained in maximizing the echo from a particular target by the use of different antennas for transmitting and receiving. It is possible to design an antenna which, when used for transmitting and receiving, will make the radar system "blind" to a particular target. Discrimination between rain and aircraft echo response will be dependent upon differences in the form of the scattering matrices of the two targets. If rain can be considered an isotropic target, the maximum echo from non-isotropic aircraft will be simultaneously achieved with zero return from rain, using either right or left-handed circularly polarized antennas, depending upon the nature of the target.

A systematic study can be made of the polarization properties for various aspects of a given target by the use of constant echo curves on a polarization chart, and the optimum polarization for a range of aspects thus determined. Use of a polarization sphere, upon which each point corresponds to an elliptical polarization, simplifies the form of the constant echo curves and aids in classifying target properties.

Determination of the scattering matrix of a target by the use of amplitude measurements alone, is possible. Seven amplitude measurements are necessary to determine all components. Present equipment and measurement techniques are adaptable to this method.

E. PROGRAM FOR NEXT INTERVAL

Simple wire arrays will be constructed with predictable scattering matrices, and measurements of polarization properties compared to theoretical predictions.

Possibility of measuring circularly polarized echo returns will be studied.

Theoretical analysis to determine optimum polarization or polarizations for completely general targets to eliminate "blind" aspects of target, if possible.

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G. IDENTIFICATION OF TECHNICIANS

MAN HOURS WORKED:	April	May	June	Total
Alvin Buttler, *Technician*	80	88	126	294
Edward Kennaugh, *Project Engineer*	160	176	168	504
Philip D. Russo, *Clerk*	20	22	21	63
M. Frances Nichols, *Computer*	80	88	84	252
V. H. Rumsey, *Supervisor*	30	32	31	93
Peter D. Young, *Technician*	80	88	84	252
L. R. Schweikart, *Machinist*	80	88	168	336
R. C. LeCraw, *Engineer*	80	88	106	274
Robert N. Tuvell, *Clerk*	111	86	103	300
Lawrence S. Ulrey, *Draftsman*	80	88	84	252
Norman Schwandt, *Machinist*	80	88	84	252
Louis R. Taylor, *Technician*	---	---	100	100
H. M. Valentine, *Machinist*	---	---	88	88
John Rowe, *Plumber*	4	---	---	4
Glen F. Fuller, *Plumber*	4	---	---	4
	889	932	1247	3068

NEW PERSONNEL:

LOUIS LEGRAND TAYLOR, Technician

Education:

North High School, Columbus, Ohio, 1944; Denison University, 1946 to 1948; The Ohio State University, July 1948 to the present.

Experience:

U. S. Army, 1944 to 1946; The Ohio State University Experiment Station, September 1949 and December 1949; Antenna Laboratory, 12 June 1950 to the present.

NOTE: In submitting this report it is understood that all provisions of the contract between The Foundation and the Cooperator and pertaining to publicity of subject matter will be rigidly observed.

Investigator........Edward M. Kennaugh........ Date...18 July 1950

Investigator........R. Conway LeCraw........ Date...18 July 1950

Investigator.. Date......................

Investigator.. Date......................

Investigator.. Date......................

Supervisor........V H Rumsey........ Date...18 July 50

FOR THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

Executive Director.....James S. Owens........ Date...7-28-50

F.E.S.